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               STUDIES OF SPONTANEOUS MAGNETIC FIELDS IN LASER-PRODUCED PLASMA--ETC(U)
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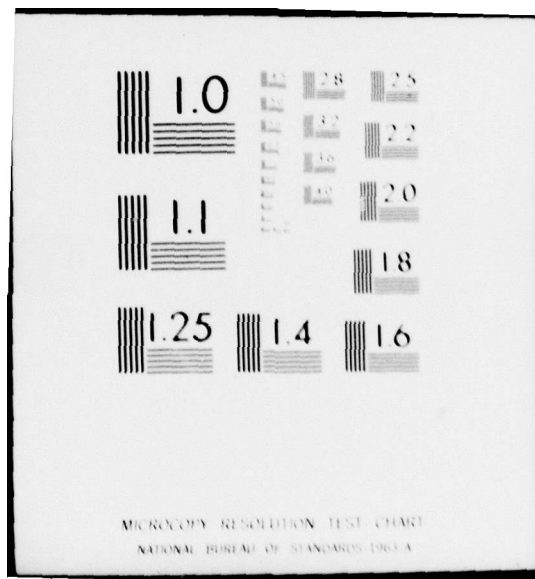
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NRL Memorandum Report 3758

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Studies of Spontaneous Magnetic Fields in Laser-Produced Plasmas by Faraday Rotation.

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Laser Plasma Branch
Plasma Physics Division

(9) Interim rept.,

(14) NRL-MR-3758

(11)   April 1978   (12) 9 p.

NAVAL RESEARCH LABORATORY
Washington, D.C.

251 950

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NRL Memorandum Report 3758	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) STUDIES OF SPONTANEOUS MAGNETIC FIELDS IN LASER-PRODUCED PLASMAS BY FARADAY ROTATION		5. TYPE OF REPORT & PERIOD COVERED Interim report on a continuing NRL problem.
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J.A. Stamper, E.A. McLean and B.H. Ripin		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Research Laboratory Washington, D.C. 20375		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NRL Problem H02-29A
11. CONTROLLING OFFICE NAME AND ADDRESS Department of Energy Washington, D.C. 20585		12. REPORT DATE April 1978
		13. NUMBER OF PAGES 15
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Work performed at the Naval Research Laboratory under the auspices of the Department of Energy.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Faraday rotation
Magnetic field
Parameter studies

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An extensive study has been made of the large magnetic fields in the plasma near the focus of a high irradiance Nd-laser beam. The dependence of the magnetic field on many experimental conditions is noted — particularly timing and the presence of a pre-formed plasma. The data were obtained with a Raman-shifted, three-channel Faraday rotation diagnostic system.

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Studies of Spontaneous Magnetic Fields in Laser-Produced

Plasmas by Faraday Rotation

We report in this letter the first broad-scale study of the large
magnetic fields produced in the focal region of a high irradiance
Nd-laser incident on a solid target. The study utilized a Raman-shifted
probing beam with a 3-channel Faraday rotation diagnostic system. The
first Faraday rotation measurements[1] (in which magnetic fields in the
megagauss range were observed) were reported in 1975. It was recognized
that these fields could (primarily through their effect on thermal
transport) play an important role in the physics of laser-fusion.[2,3]
Recently, there has been considerable theoretical interest in these
fields[4-7] -- particularly in relation to resonant absorption. However,
although several laboratories[8-12] have undertaken further Faraday
rotation studies, there has been no published confirmation. This has
led to some doubt about the magnitude and importance of the fields.
Thus, the studies reported here are of particular significance. These
Faraday rotation studies have given reliable results for a variety of
experimental conditions (timing, target material and geometry, laser
irradiance and polarization, focal position, and pre-pulse effect) and
have provided insight into the experimental conditions required for
observing the fields.

1

At high laser irradiance ($\sim 10^{16}$ W/cm^2), the second harmonic emission (5320 Å) from plasmas produced by our Nd-glass laser was so intense that a second harmonic probe beam could not be used successfully (as it was at lower irradiance) for Faraday rotation studies. An analogous problem was also encountered at the third harmonic.[12,13] However, the present experimental arrangement (shown in Fig. 1) uses a non-harmonic wavelength (6329 Å) to overcome the emitted light problem. This was obtained by Raman-shifting the second harmonic probe beam in an ethanol cell.

The Raman-shifted probing beam (pulse width $\sim$ 50 psec) is optically delayed to allow variation of the relative timing between the probe pulse and the main laser pulse. The vertically-polarized probing beam is concentrated into the interaction region with an f/300 aperture lens. A diffraction-limited, f/2 lens is used to collimate the probing beam which has passed through the plasma. The collimated beam is then split into 3 beams with a 5° quartz wedge. These beams are focused (with separate 2-m focal length lenses) and pass through 3 independently oriented polarization analyzers (plastic sheet polarizers) to provide 3 channels of information. Space-resolved images are recorded (at focus) on Polaroid film. Thus, experimental correlations are available among the 3 channels to rule out any effects due to density gradients or transverse magnetic fields.[14]

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The targets were irradiated with a beam from the NRL Pharos II Nd-laser system.[15] The output pulses (~ 5 J) with pulse duration of 75 psec (FWHM) were focused with an (aspheric) f/2 lens to a half-energy focal diameter of 25 um, yielding an average irradiance of 10^{16} W/cm^2. Data were taken using polystyrene, $(CH)_n$, and steel (razor blade) slab targets and using polystyrene spherical targets.

Probe beam timing was varied with respect to the peak of the main laser pulse. Faraday rotation of the probing light was observed (for the steel targets) as early as + 15 psec, maximized near + 50 psec and then decreased (but could be seen as late as + 450 psec). The dependence of the magnetic fields on timing was not strongly correlated with target material. The data presented here were all obtained at the + 50 psec timing. Data were also taken with and without a pre-pulse on the incident laser beam and this, as shown later, proved to be an important effect. Laser irradiance was lowered by about an order of magnitude either by moving the focal position with respect to the target or by attenuating the laser beam energy. In both cases, the low irradiance shots showed no observable Faraday rotation. However, a pre-pulse was not used and timing was not varied on the low irradiance shots. All of the remaining data presented here were obtained with the target at good focus.

An attempt was made to observe the magnetic fields associated with resonant absorption.[5,6,7] Data were taken at early times (-15 to + 15 psec) using a tilted (20°) iron target so oriented that the main laser beam was in either an s or p polarization state with respect to the

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density structure. No effect was observed, perhaps indicating that the probe beam did not sample close enough to the critical region.

The trend of variation of the Faraday rotation data with target material, target geometry, and a laser pre-pulse is illustrated in Figs. 2 and 3. Each photograph shows the actual orientation of the target when looking into the probing beam with the main laser beam incident from the right. The orientation of each polarization analyzer (with respect to the incident polarization) is indicated (in degrees) under the photograph. The analyzer orientation and Faraday rotation angle are both taken, viewing into the probing beam, as positive when counter-clockwise. The rotation angle for a given region on the photograph can be estimated by comparing the exposure (varying as the square of cosine of the angle between the beam polarization and analyzer) at that region with that of the background.

Results for slab targets are shown in Fig. 2. The photographs in the top row are for a polystyrene target irradiated by a single 3.5 J laser pulse. Note the well-localized bright regions above or below center. These correspond to light that has been Faraday rotated to give locally enhanced transmission through the analyzer. The up-down asymmetry and its reversal with analyzer orientation are consistent with thermally generated magnetic fields[16,17] -- oriented azimuthally about the laser beam axis. Similar results were obtained for slab steel targets with a single laser pulse. A pre-pulse containing 3% of the total 4.4 J energy irradiated the same target 2 nsec ahead of the

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main pulse for the results shown in the second row. The presence of the preformed plasma due to the pre-pulse increased the intensity and spatial extent of the rotated light, without affecting the magnetic field orientation. A distinct darkening below the background level exists vertically opposite to the bright region. This, too, is consistent with azimuthally oriented magnetic fields since the rotated light in that region is closer to a cross-polarized state than is the background. The bottom row of photographs (in Fig. 2) is also a 3ω pre-pulse case (of 6.5 J total) but using a steel (razor blade) target. Here, with both a pre-pulse and a higher atomic number target, the Faraday rotation was most observable and had the largest spatial extent. However, one should distinguish between observability and magnitude of the magnetic fields -- the latter being difficult to determine precisely.

Earlier studies at NRL[18] showed that a prepulse could have a marked effect on both x-ray and fast ion production. The rather dramatic effect of a pre-pulse on backscatter[19] could be understood in terms of its effect on the density gradient. It is possible that density modification by the pre-pulse, via the thermally generated magnetic fields and their effect on thermal transport, could account for the observed pre-pulse effect on x-rays and fast ions.

Faraday rotation results for single-sided irradiation of spherical polystyrene pellets are shown in Fig. 3. The top and bottom row of photographs were taken on shots when irradiated, respectively, with a 2 J (no pre-pulse) and 3.3 J (3ω pre-pulse) main pulse. The pronounced effect of a pre-pulse is again present. Structure at the rear of the

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pellet on pre-pulse shots may have been due to some of the pre-pulse energy being transmitted through the polystyrene. The presumably unpolarized light there and in other parts of the photographs may be due to some depolarization of the probe beam (e.g., due to density gradients or magnetic fields[14]) or an intense plasma light emission. Note, that for the pellets as well as slabs, a reversal of the analyzer orientation always produces a corresponding reversal in the position of the bright region.

The direction of the magnetic field can be determined from the sense of Faraday rotation. The observed asymmetry is found to be consistent with the direction $\nabla T \times \nabla n$ of a thermally generated magnetic field where ∇T is cylindrically in toward the laser axis, and ∇n is into the target, i.e., the magnetic field is clockwise when looking in the direction of the main laser beam. The azimuthal direction was unchanged throughout the observation interval (+ 15 to + 450 psec) and is consistent with theoretical calculations[17] including the thermal force term.

The magnitude of the Faraday rotation angle θ along a path z can be estimated (when $\omega_c/\omega \ll (\omega/\omega_p)^2 - 1$) from

$$d\theta/dz = \omega_p^2 \omega_{cz}/2\bar{n}\omega^2 c, \tag{1}$$

where ω_{cz} is the z-component of the electron cyclotron frequency, $(\bar{n})^2 = 1 - (\omega_p/\omega)^2$, and ω_p and ω are, respectively, plasma and probe frequencies. For a given density profile and a reasonable model of the magnetic field variation, one can estimate the magnitude of the magnetic field by integrating Eq. (1) along the probe beam path.

There were two experimental inputs to the density evaluation: interferometry and the extent of the dark region in the Faraday rotation photographs. This dark region results from rays being refracted out of the solid angle of the collection optics. Density structure was determined by Abel-inversion of interferograms[20] taken with an f/4 collector but with the same target and laser conditions as the f/2 Faraday rotation data. The density was modeled by a spherical variation $\exp[-(r-r_o)/L]$ where the density scale length L is extrapolated over a radial distance of 10-12 um from the interferometry. The radius r_o of the critical density is then determined by requiring that a ray having the observed radius s (of dark region) at the turning point will be refracted through an f/2 collection angle ($\sim 14°$). The magnetic field is also assumed to vary exponentially[17] with radius but with a scale length that is computed (with this density structure) from the observed radial variation of the Faraday rotation angle.

For example, the data for Shot 3662 onto a spherical pellet (shown in the lower half of Fig. 3) gave a Faraday rotation angle of $8°$ at a radius s of 80 um and decreased to $2°$ at a radius of 100 um.

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Interferometry showed that L was less than 40 μm which required that the

sampled magnetic field (at the turning point) be greater than 0.4

megagauss. A more probable value for this magnetic field (for

$L = 20 \pm 5$ μm) is 0.6 ± 0.1 MG.

Some guidance can be given concerning the experimental conditions

required for detecting Faraday rotation. We have found it is important

to use a high-intensity, non-harmonic wavelength probe and look at an

optimum time after arrival of the main laser pulse. The presence of a

prepulse greatly enhanced the observability of the magnetic fields. The best

results were also obtained for a small but non-zero deviation from the

cross-polarized analyzer orientation. In fact, good data was not

obtained in our previous studies with a cross-polarized Wollaston prism

analyzer. This may be due to the fact that maximum contrast is not

obtained, for a slightly depolarized beam, at the precise cross-

polarized orientation.

In summary, a study utilizing a 3-channel Faraday rotation

diagnostic system has shown the dependence of thermally generated

magnetic fields on a variety of experimental parameters. Correlations

between the channels, completely consistent with these fields for all

the 72 data shots, gives a high level of confidence in the results.

Acknowledgments

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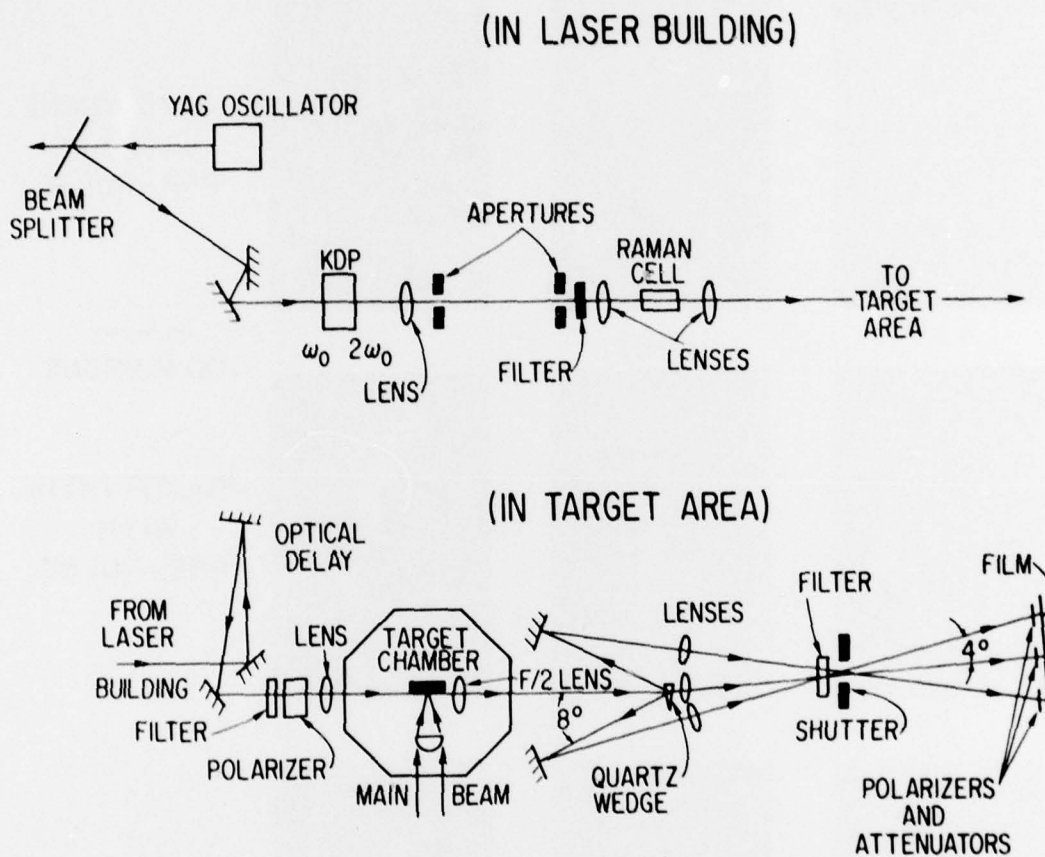
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(IN LASER BUILDING)

(IN TARGET AREA)

Fig. 1 — Diagram of experimental arrangement

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POLYSTYRENE
WITHOUT
PRE-PULSE

+75   +82$\frac{1}{2}$ -75

100 MICRONS

POLYSTYRENE
WITH
PRE-PULSE

+75   +82$\frac{1}{2}$ -75

RAZOR BLADE
WITH
PRE-PULSE

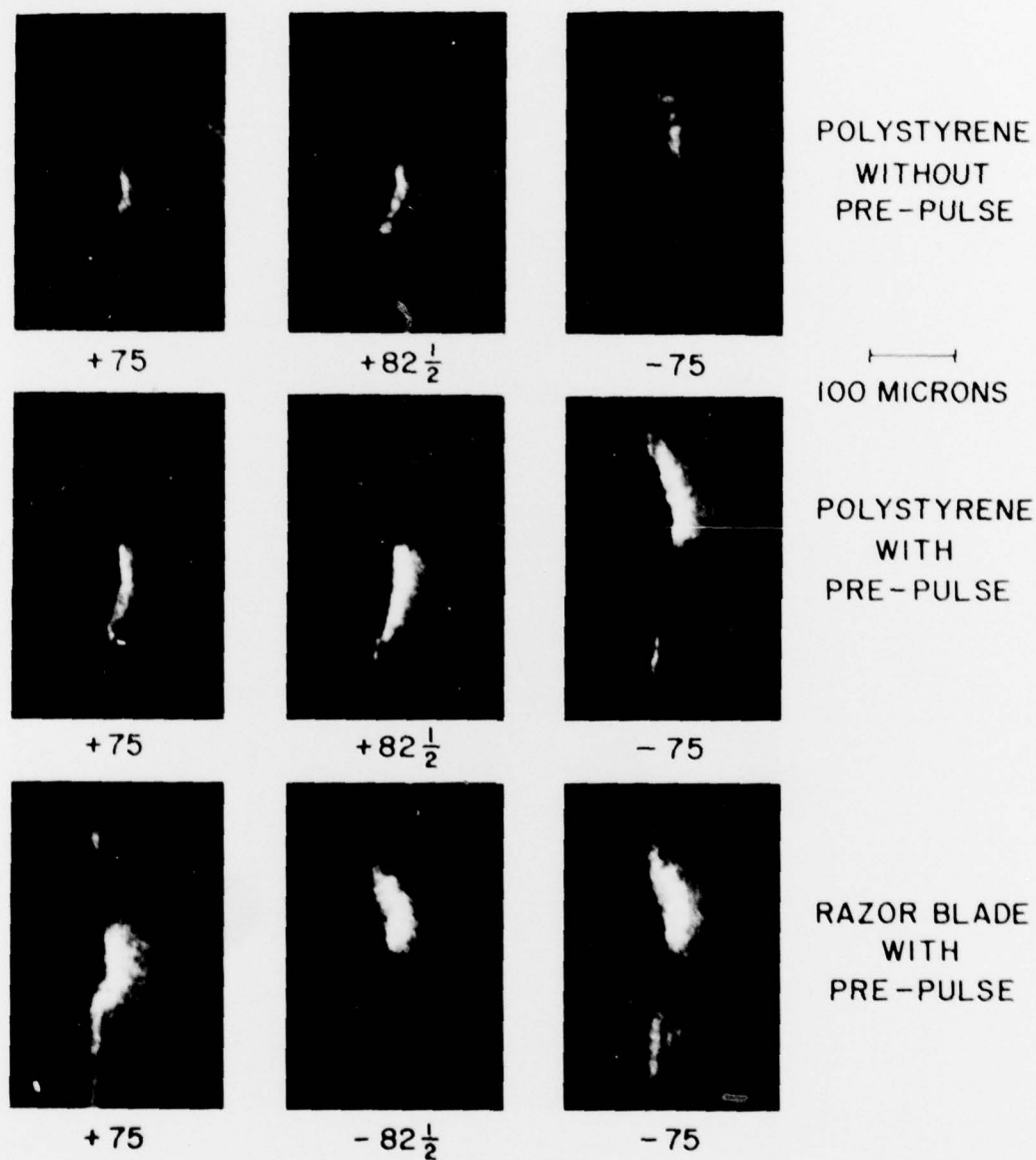+75   -82$\frac{1}{2}$ -75

Fig. 2 — Faraday rotation photographs for slab targets, without and with pre-pulse. View is into probing beam with main laser beam incident from the right. Analyzer orientation (with respect to the incident polarization) is shown below each photograph. The position of rotated light (bright region) reverses with reversal of analyzer orientation. Probe pulse timing was + 50 psec.

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WITHOUT
PRE-PULSE

├─────┤
100 MICRONS

WITH
PRE-PULSE

+75 $-82\frac{1}{2}$ -75

+75 $+82\frac{1}{2}$ -75

Fig. 3 — Faraday rotation photographs for spherical polystyrene targets, without and with pre-pulse. View, analyzer orientation, and timing are as in Fig. 2.

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